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A combined theoretical and experimental research program on "Correlation-induced Frequency Shift from Rough Surface Scattering" has been implemented. This study has increased our understanding of localization, coherence and fluctuation from rough surface scattering. The results should have potential application in radar signature, telecommunication, remote sensing, satellite tracking, mine detection and target acquisition and classification.

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CORRELATION-INDUCED FREQUENCY SHIFT FROM ROUGH SURFACE SCATTERING

FINAL REPORT FOR PERIOD COVERING SEPTEMBER 1998 THROUGH OCTOBER 2001

Prepared for:

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Prepared under:

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Author:

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1.0 STATEMENT

Surface Optics Corporation (SOC), in association with UC Irvine, Department of Physics, has been conducting a combined theoretical and experimental research program for Correlation-Induced Frequency Shift from Rough Surface Scattering. It has been assumed until recently that the spectrum is an intrinsic property of radiation that does not change due to propagation of radiation in free space. That this assumption may not always hold true was suggested in a recent investigation by Wolf[1] who predicted that the spectrum of light will, in general, be different at various points in space. In fact, this new concept of spectral variance, which in some cases is manifested as a frequency shift of spectral lines, has challenged the traditional principles of modern optics, and has several important consequences and applications in both science and engineering.

Although there has been much work done in Correlation-induced spectral changes, a significant contribution has been accomplished for spectral coherence from rough surface scattering. We have initiated research on the angular spectrum redistribution from rough surface scattering and show a large spectral change of light scattered from a bounded medium with random surface. We also show near-field and far-field changes in the spectrum of light scattered from a randomly rough surface and in the Otto attenuated total reflection configuration. We have demonstrated the angular spectrum redistribution from a real image of a light as a secondary source and compared the spectral redistribution of rough surface scattering from different lasers (single scattering phenomena) and from different reflection direction (multiple scattering phenomena).

We have shown a new feature of angular intensity correlation functions $C^{(1)}$ and $C^{(10)}$ from rough surface scattering. Also, a localized defect from random rough surfaces has been detected with a pulsed laser beam and the angular intensity correlation function. Amplified enhanced backscattering through a gain medium bounded with 1-D and 2-D rough surfaces are investigated and enhanced backscattering at grazing angle is measured.

The fabrication of one-dimensional metallic surfaces that act as band-limited uniform diffusers has been recently carried out. Experimental results for the angular dependence of the intensity of the light scattered from them show that these surfaces give rise to a scattered intensity that is nonzero only within a prescribed angular region.

The principal goal of this study is to increase our theoretical understanding of localization, coherence, and fluctuation from rough surface scattering. Concurrently, the results should have potential applications in remote sensing, radar signature, optical tagging, telecommunication, and target acquisition and classification.

2.0 SUMMARY OF PREVIOUS RESEARCH

During the period from 16 September 1998 through 30 October 2001 under Grant DAAG-55-98-C-0034, we have investigated "Correlation-induced Frequency Shift from Rough Surface Scattering". The advances in our understanding of such phenomena are summarized as follows.

2.1 Angular Spectrum Redistribution from Rough Surface Scattering

2.1.1 Changes of light scattered from a bounded medium with random surface

It was predicted just over a decade ago that the spectrum of the light in the far-field emitted by a three-dimensional quasihomogeneous source can differ from that of the source if the spectral coherence of the latter is appropriately chosen, even if the light propagates in free space.(1)

In order to obtain large enough changes in the spectrum of light scattered from a random medium that they can be measured it is desirable for the angular dependence of the intensity of monochromatic light scattered from it to possess features that depend strongly on the frequency of the incident light. The backscattering enhancement peak does not possess this feature – it is always in the retroreflection direction – only its width does. A scattering system that does possess such features is a film, either free-standing or supported, that supports two or more guided or surface waves. If the illuminated surface of the film is a one-dimensional randomly rough surface, the angular dependence of the intensity of light scattered incoherently from the film, or transmitted incoherently through it, will display satellite peaks on both sides of the enhanced backscattering and enhanced transmission peaks.(2) The scattering angles at which the satellite peaks occur depend on the frequency of the incident light, and this dependence can be quite strong.

In recent theoretical calculations p-polarized light whose spectral density was described by a Gaussian form with a central frequency ω_0 and half-width $\Delta\omega$ was scattered from a ZnS film deposited on the planar surface of a perfect conductor. The illuminated surface of the film was a one-dimensional randomly rough surface. The film supports four guided waves that give rise to eight satellite peaks in the angular dependence of the intensity of the incoherent component of the scattered light, when the light is incident normally on the film, in addition to the enhanced backscattering peak. These satellite peaks give rise to marked shifts away from ω_0 of the position of the maximum of the spectrum of the scattered light for scattering angles in their vicinity. The magnitude of the relative shift in the position $\omega_m(\theta_s)$ of the maximum of the spectrum of the scattered light as a function of the scattering angle θ_s, $|\omega_m(\theta_s) - \omega_0| / \omega_0$, can reach a value as large as 0.12 for θ_s in the vicinity of the angle at which a satellite peak occurs, when $\Delta\omega/\omega_0 = 0.05$. For narrower band widths, corresponding to natural laser sources, the shifts are smaller, e.g. at $\theta_s = 0°$ $(\omega_m - \omega_0)/\omega_0 = -4.4 \times 10^{-4}$ for $\Delta\omega/\omega_0 = 4 \times 10^{-3}$. Even so, they are still about two

orders of magnitude larger than those predicted for disordered volume scattering for the same values of $\Delta\omega/\omega_0$.

2.1.2 Near-field and far-field changes in the spectrum of light scattered from a randomly rough surface

In earlier calculations of spectral (Wolf) shifts of light scattered from randomly rough surfaces,[3] these shifts were calculated from the incoherent component of the scattered field in the far zone, where it is formed by the radiative components of the scattered field. However, in view of the fact that only a source possessing a very special spectral coherence can give rise to radiated light whose spectrum is not shifted from that of the source as it propagates away from the source,[4] it was expected that the spectrum of scattered light measured at any distance from the scattering system should differ from that of the source. In particular, the spectrum of light scattered from a randomly rough surface, measured in the near-field region, i.e., at a sub-wavelength distance from the surface, should be an interesting object of study, because it includes contributions from the evanescent, non-radiative components of the scattered field, which never reach the far-field region, as well as from the radiative components, which do.

The evolution of the relative spectral shift $(\omega_m(\theta_s) - \omega_0)/\omega_0$ was calculated for the case where s-polarized light of central wavelength $\lambda_0 = 2\pi c/\omega_0 = 632.8$ nm was incident normally on a rough $BaSO_4$ film deposited on the planar surface of a perfect conductor. This structure supports two guided waves, which in the far zone give rise to two satellite peaks, in addition to an enhanced backscattering peak. It was found that at any distance from the random surface the spectrum of the scattered light was red-shifted, but the angular dependence of the shift changed considerably with increasing distance from the surface. In the near zone no coherent phenomena (enhanced backscattering, satellite peaks) were reflected in the dependence of $(\omega_m(\theta_s) - \omega_0)/\omega_0$ on θ_s: they form only in the far zone. At a distance of $50\lambda_0$ from the surface strong shifts in the vicinity of scattering angles at which satellite peaks occur were observed, as well as in the vicinity of peaks associated with single-scattering processes, where they reached a value of $|\omega_m(\theta_s) - \omega_0|/\omega_0 \cong 0.05$. Even in the near zone relative Wolf shifts as large as 0.014 were obtained.[5]

2.1.3 Spectral changes in the Otto attenuated total reflection configuration

A recent theoretical investigation of the spectral shifts of light scattered from the one-dimensional random surface of a dielectric film deposited on the planar surface of a perfect conductor showed that they could be quite large for scattering angles in the vicinity of the angles at which satellite peaks occur in the angular dependence of the intensity of the incoherent component of the light scattered from this system, when it is illuminated by monochromatic light.[6] These satellite peaks are a consequence of the several waveguide modes supported by the scattering system.[7] This result prompted a search for other structures bounded by a random surface that could produce large spectral shifts of light scattered from them. Such a

structure is a semi-infinite metal with a one-dimensional randomly rough surface that is separated by a sub-wavelength air gap from the planar base of a prism through which the metal surface is illuminated – the Otto attenuated total reflectance (ATR) configuration.[8] The angular dependence of the intensity of p-polarized light of frequency ω_0 scattered from this system displays sharp intense peaks at scattering angles at which the optimal radiation of the surface plasmon polaritons of frequency ω_0 supported by the air-metal interface occurs. P-polarized polychromatic light of central frequency ω_0 incident normally on the Otto ATR configuration was found to be blue-shifted when scattered into the retroreflection direction. However, for scattering angles in the vicinity of the angles at which the optimal radiation of surface plasmon polaritons occurs, ± 34.7° for the system studied, namely a fused silica prism and a silver substrate, the spectrum of the scattered light was blue-shifted when the scattering angles was smaller in amplitude than these angles, but was red-shifted when it was larger in magnitude than these angles. The magnitudes of the latter shifts were quite large: the relative shift $(\omega_m(\theta_s) - \omega_0)/\omega_0$, where $\omega_m(\theta_s)$ is the position of the maximum of the spectrum of the scattered light as a function of the scattering angle θ_s, could reach a value of 0.025, when the linewidth of the incident light $\Delta\omega$ was $\Delta\omega/\omega_0 = 0.05$. Shifts of this magnitude are large enough to be measured.[9]

2.1.4 Angular spectrum redistribution from a real image of a light as a secondary source

Coherence theory predicts that the correlation in the fluctuations of a source distribution can cause frequency shifts in the spectrum of the emitted radiation, even when the source is at rest relative to the observer. Recently, we measured angular spectrum redistribution, or frequency shifts from a real image of a point source, and further verified the coherent interference effect of a fine-band source.

How would a second source from a real image of a spot of a light introduce the Wolf effect, or frequency shift? A preliminary analysis illustrates this phenomena. The impulse response function at the image plane of a light has two exponential terms

$$exp\left[j\frac{k}{4F}(x_1^2+y_1^2)\right]exp\left[j\frac{k}{4F}(x_2^2+y_2^2)\right], \qquad (2.1.4\text{-}1)$$

which will quadratically change the spectral complex degree of coherence, such that these terms will depend not only on the relative positions of the two relevant points on image plane for which the complex degree of coherence is calculated but also on their absolute positions. This apparently contradicts the Scaling law.[10]

2.1.5 Spectral coherence from rough surface scattering with a secondary source

We have a setup by using a real image of a light as a secondary source and have measured the angular spectrum redistribution from a 1-D diffuse gold with such source. We have also measured the angular spectrum redistribution from a 2-D gold mirror by imaging an Arc lamp source on the mirror, and there is a pinhole in front of

the mirror which forms a secondary source. The correlation in the fluctuation of a source distribution could cause the spectrum redistribution on propagation in free space. In general, no new photons are created.[11]

Since the impulse response function at the image plane of a light source will quadratically change the spectral complex degree of coherence, this apparently contradicts the Scaling Law. Moreover, the scattering from rough surface makes the effect significant.

2.1.6 Angular spectrum redistribution from characterized 1-D rough surface scattering with diode laser

- **Comparison of spectral redistribution of rough surface scattering from different lasers (single scattering phenomena):**

Effect of spectral and spatial coherence of light in rough surface scattering has been investigated. Recently we have measured the Wolf Effect from a randomly rough 1-D gold sample with He-Ne, Ar and Diode lasers. It was found that the Wolf Effect is more evident with a diode laser which has a wide bandwidth (~17.2 nm), and this is a single scattering phenomena.[12]

- **Spectral redistribution of rough surface scattering near the retro-reflection direction (multiple scattering phenomena):**

A measurement of a large slope 1-D gold surface with a Gaussian distributed diode laser, ω_0 = 651.21 nm, $\Delta\omega$ = 17.2 nm, shows a strong red shift peak nearby the backscattering direction. Since the angular peak width of the enhanced backscattering is proportional to $\Delta\theta_s \cong \lambda/d$ where d is the mean free path of the multiple scattering. The longer the wavelength, the wider the enhanced backscattering peak width, which is why the ensemble of realization of all the wavelengths introduces the red shift near the backscattering direction.

Figure 2.1.6-1 shows the measurements.[12]

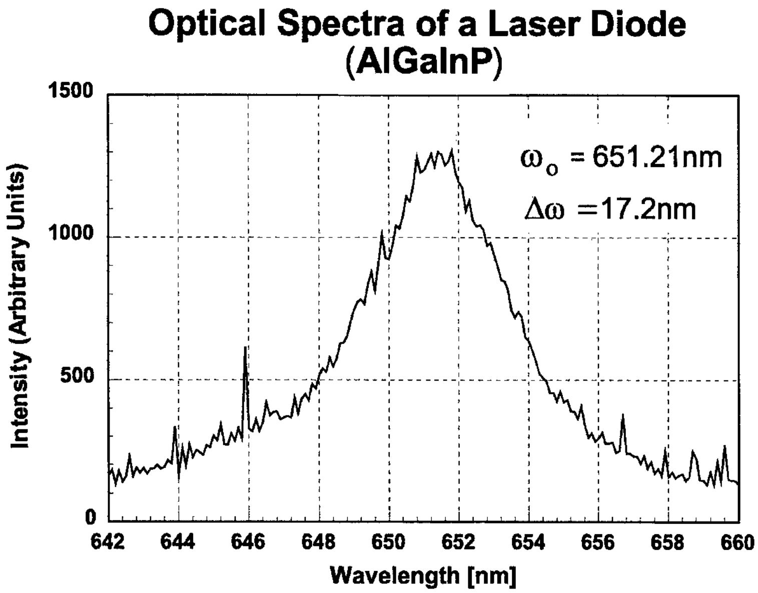

Figure 2.1.6-1 (a). Optical spectra of a laser diode where $\Delta\omega/\omega_0 \cong 2.6 \times 10^{-2}$.

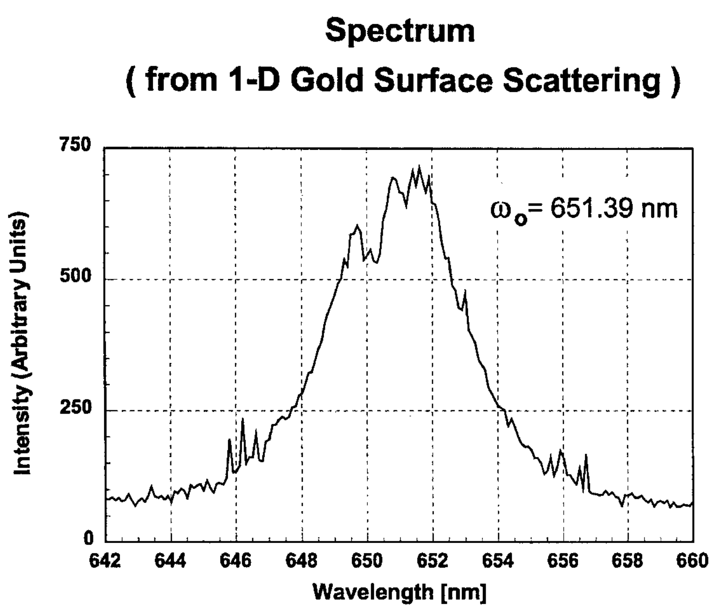

Figure 2.1.6-1 (b). **Spectrum redistribution, where $\Delta\omega_s \cong 0.18$ nm and $\Delta\omega_s/\omega_0 \cong 2.76 \times 10^{-4}$ at $\theta_i = 5°$, $\theta_s = -7°$, and $\sigma = 1.51$ μm, $a = 4.0$ μm.**

2.2 New Features of Angular Intensity Correlation Function from Rough Surface Scattering

The memory effect $C^{(1)}$ and the time-reversed memory effect in the angular intensity correlation function of p-polarized light scattered from a dielectric film (photoresist) deposited on a glass substrate have been investigated experimentally.[13] The vacuum-dielectric interface is a one-dimensional randomly rough interface, while the dielectric-glass interface is planar. A CCD camera was used to record the speckle pattern in the specular direction for each angle of incidence, and the angular intensity correlation function was then calculated from the digitalized images. The resulting correlation function displayed two well-defined peaks, one of which was the memory effect peak, and the other of which was the reciprocal memory effect peak. These peaks contain much the same information as the enhanced backscattering peak. However, their observation is much simpler because they can occur far from the retroreflection direction.

The memory effect $C^{(1)}$ has also been observed experimentally in the angular intensity correlation function of light scattered in its double passage through a random phase screen.[14] The theory of this effect had been worked out by H. Escamilla, E.R. Méndez and D. Hotz.[15] The manner in which the speckle pattern is predicted to move as the source is moved and the symmetry of speckles around the backscattering direction are verified experimentally.

The function $C^{(10)}$ has been overlooked in earlier studies due to the use of the factorization approximation, which presents a new type of memory effect, and its magnitude is comparable with that of $C^{(1)}$. $C^{(10)}$ can be observed if the following is satisfied:

$$\sin\theta_{i1} + \sin\theta_{i2} = \sin\theta_{s1} + \sin\theta_{s2} \ . \qquad (2.2\text{-}1)$$

If we set θ_{i1} is equal to θ_{i2}, and θ_{s1} is equal to $\theta_{i1} + \Delta\theta$, then θ_{s2} should be $\theta_{i1} - \Delta\theta$ which locates on the other side of the specular direction ($-\theta_{i1}$) and is symmetrical to θ_{s1} around the specular direction. The experimental results were presented to verify the validity of the theoretical analysis. For a two-dimensional photoresist film on the glass substrate, the incident laser is He-Ne with wavelength at 0.6328 microns, the incident angle θ_{i1} is 20° and the scattering angle θ_{s1} is -10°. The surface profile of the sample was measured with the standard deviation of heights σ is approximately 110Å and the $1/e$ value of the correlation length is approximately 2800Å.

The specular direction is at θ_{s2} = 20°, we find the correlation function $C^{(10)}$ is symmetrical around the specular direction. Since the far-field low-order scattered amplitude is proportional to the Fourier transform of the real surface profile, which is Hermitian function, therefore the far-field scattered intensity should be symmetrical with respect to the specular direction. The low-order angular correlation function $C^{(10)}$ is proportional to the correlation of the scattered intensity, therefore $C^{(10)}$ is symmetrical around the speckle direction.[16]

Although the angular intensity correlation functions calculated from the scattering of light from 1-D and 2-D random metal surfaces display the $C^{(1)}$, $C^{(10)}$, $C^{(1.5)}$,

$C^{(2)}$, and $C^{(3)}$ correlations,[17] the $C^{(1.5)}$, $C^{(2)}$, and $C^{(3)}$ correlation functions remain unobserved at the present time, and their measurement poses a challenge to experimentalists.

2.3 Amplified Enhanced Backscattering through a Gain Medium Bounded with 1-D and 2-D Rough Surface

The enhanced backscattering from organic laser gain media bounded with one-dimensional (1-D) and two-dimensional (2-D) rough metal films are investigated. Several organic optical gain materials have been prepared by doping laser active dyes in the matrix of acrylic polymers. These materials produce efficient and broadband fluorescence emission in the visible wavelengths under the pump of a pulsed YAG or CW Argon laser. These gain materials are sliced and coupled with 1-D or 2-D randomly rough gold films with a large slope. Experimental investigation is carried out using a He-Ne laser at 0.6328 μm as the scattering source with optical gain provided by a CW Argon laser at 0.515 μm. It is found that the enhanced backscattering peak is sharply increased and the width is narrowed for low values of dielectric constant $|\varepsilon_2|$. It is the first time that we have measured the satellite peaks around the enhanced backscattering peak for a very rough metal film coated on the photoresist substrate and the peaks of the amplified satellites are high and their width narrow as well. We believe that the results from an amplifying polymer bounded by a random rough surface here could be explained by the theoretical prediction of the enhanced backscattering for a leaky guided wave model with a low dielectric constant $|\varepsilon_2|$. The enhanced backscattering peak is proportional to $|\Delta|^{-1}$, and its width is proportional to $|\Delta|$, where $|\Delta|$ is the smallest decay/amplification rate of the guided waves supported by the dye-doped polymer in the presence of the surface roughness. $|\Delta|$ decreases with increasing dielectric constant $|\varepsilon_2|$. This explains that when dielectric constant $|\varepsilon_2|$ increases, the enhanced backscattering peak is sharper and its width is narrower.[18]

Theoretically we study the scattering of s-polarized light from the one-dimensional, randomly rough surface of a homogeneous amplifying dielectric medium deposited as a film on the planar surface of a semi-infinite perfectly conducting substrate. The reflectivity of the rough film is found to be greater than that of the corresponding planar film if only true guided waves supported by the scattering structure exist at the frequency of the incident light; it can be smaller than that of the corresponding planar film if a leaky guided wave also exists at the frequency of the incident light. Although the reflectivity of an amplifying film with a planar surface is greater than unity for all angles of incidence, that of an amplifying film with a random surface can be smaller than unity in a certain range of angles of incidence as a consequence of the existence of a leaky guided wave. The contribution to the mean differential reflection coefficient from the incoherent component of the scattered light displays an enhanced backscattering peak and satellite peaks (the latter if the scattering structure supports two or more guided waves). The overall intensity of the light scattered incoherently from the surface of a rough amplifying film is always greater than that of the light scattered from the same film with the same magnitude of the imaginary part of its dielectric constant, but of opposite sign, irrespective of the presence or absence of a leaky wave at the frequency of the incident light. However,

the height and width of the enhanced backscattering peak are nonmonotonic functions of the magnitude of the imaginary part of the dielectric constant of the film, when a leaky wave is present, but depend monotonically on it when no leaky wave is present. In the case of an absorbing film these functions depend monotonically on the imaginary part of the dielectric constant.[19]

2.4 Enhanced Backscattering at Grazing Angle

The backscattering signal at small grazing angle is very important for vehicle re-entrance and missile tracking applications. Rigorous calculations of the scattering of electromagnetic waves from a randomly rough surface at grazing angles of incidence present a challenging computational problem. This is due at least in part by the fact that if, say, a one-dimensional random surface is illuminated by a beam of finite width W, its intercept with the means scattering surface $g = W/\cos\theta_0$, where θ is the angle of incidence measured counter-clockwise from the normal to the mean scattering plane, increases to a very large value as θ_0 approaches 90°. For example, if θ_0 = 89°, g = 57.3 W. The length L of the random surface generated numerically in computer simulation studies of rough scattering is usually taken to be 4-5 g, to avoid end effects. Thus, surfaces for which L is as large as 280W, or greater. From an experimental point of view, we have to prepare a sample with its size as large as 58W for angle of incidence of the order of 89°.

In the experiment, the sample we used is a smooth aluminumlate that was coated with a dielectric film for high performance and protection. The thickness of the layer is approximately 5.2 μm. The dielectric constant of Al at λ = 0.6328 μm is ε_1 = −56.52 and ε_2 = 21.25. The dielectric constant of film is n = 1.64. The rms height of the roughness of the film is about 60Å and $1/e$ correlation length is about 3000Å. The illuminating source in the experiment is a 15 mW He-Ne laser with λ = 0.6328 μm.

Figure 2.4-1 shows the experimental results for p-polarization which shows a large enhanced backscattering peak at θ_s = 89°. Due to Quetelet's rings, the energy of diffusion is redistributed and a large portion of energy is attracted to the retro-reflection direction at grazing angle.[20]

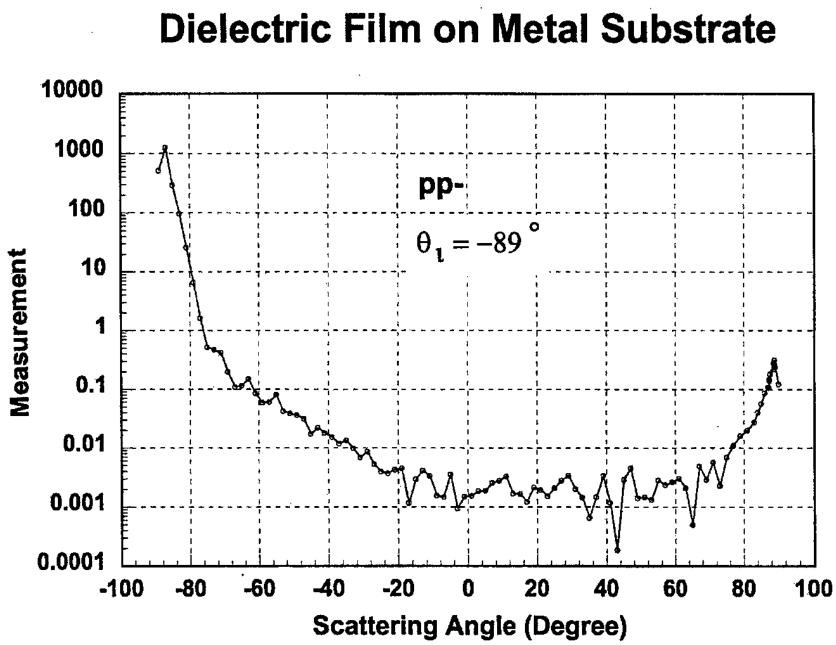

Figure 2.4-1.

2.5 Design of Band-limited Uniform Diffusers

For many practical applications it is desirable to have optical diffusers whose light scattering properties can be controlled. In particular, a nonabsorbing diffuser that scatters light uniformly within a range of scattering angles, and produces no scattering outside this range, would have applications, for example, to projection systems, where it is important to produce even illumination without wasting light. Such an optical element is called a *band limited uniform diffuser.*

Two approaches to generating numerically one-dimensional random surfaces that act as band-limited uniform diffusers have been created recently. On the basis of the geometrical optics limit of the Kirchhoff approximation it was shown that one-dimensional random surfaces with this property are characterized by a probability density function (pdf) of slopes that is constant within a prescribed range of slopes and vanishes outside it. In the first approach the surface was generated by centering ridges of trapezoidal cross-section on equally spaced lines of a planar substrate with weights that were obtained from a pdf that is directly related to the desired pdf of slopes of the surface. In the second approach the derivative of the random surface was obtained from the stationary solution of the problem of tracking the coordinate of a particle that executes a one-dimensional random walk between two perfectly reflecting walls, in which the probabilities of the particle jumping to the right or to the left, or staying at its site, at the i^{th} time step, are related to the desired pdf of slopes of the surface. The surface itself was then obtained by a numerical integration. Rigorous computer simulations of the scattering of s-polarized light from perfectly conducting surfaces generated by both of these approaches showed that the resulting scattered intensity is indeed constant within the prescribed range of scattering angles

which, at normal incidence, can be as small as $-1° < \theta_s < 1°$, and is zero outside this range.

The fabrication of one-dimensional metallic surfaces that act as band-limited uniform diffusers has recently been carried out. Experimental results for the angular dependence of the intensity of the light scattered from them show that these surfaces give rise to a scattered intensity that is nonzero only within a prescribed angular region, but they do not yet give rise to a constant intensity within this region. It is believed that this feature can be corrected by increasing the length of the fabricated surface.(21)

2.6 Scattering of Pulsed Beams from Surface Defects

The experimental detection of the electromagnetic resonances supported by surface defects is not an easy task. In recent work(22) on the scattering of p- and s-polarized light from a rectangular groove ($x_3 = -h$, $|x_1| < d/2$; $x_3 = 0$, $|x_1| > d/2$) on a perfectly conducting surface showed that most of the structure (dips) observed in the scattered intensity as a function of the wavelength of the incident light for fixed angles of incidence and scattering is not due to the excitation of the electromagnetic resonances supported by the groove, but arises at wavelengths at which the total electric field or the normal derivative of the total magnetic field in the throat of the groove, ($x_3 = 0$, $|x_1| < d/2$) nearly vanishes, so that the entire planar $x_3 = 0$ acts almost as a perfect mirror, and scattering away from the specular direction becomes very small at these wavelengths. Moreover, these dips can significantly mask the dips associated with the excitation of the electromagnetic resonances. In a recent paper it was predicted that these resonances can be detected experimentally in studies of the scattering of sub-picosecond electromagnetic pulses from the surface defects that support them. When the central wavelength of the pulse matches the wavelength of one of the resonances, an exponential tail is present in the time dependence of the intensity of the scattered field, whose decay time is the lifetime of the resonance. This exponential tail disappears when the central wavelength of the pulse is shifted away from the wavelength of the resonance. An exponential tail, observed in the intensity of the pulse scattered away from the surface unambiguously indicates the presence of a resonant scatterer or scatterers, irrespective of the type of scatterer (groove, ridge, etc.), the type of substrate (perfect conductor, metal, etc.), or the polarization of the incident electromagnetic field. Thus, the approach described is free from the ambiguities that arise when a cw source is used.(23)

2.7 Scattering of Electromagnetic Waves from a One-dimensional Random Metal Surface with a Localized Defect

Two experimental investigations have been carried out of the angular intensity correlation function of the light scattered when a polarized beam of light is incident from vacuum on a one-dimensional rough surface. One part of the surface used consisted of a dielectric film (photoresist) deposited on a glass substrate, while the other part was identical to the first except for the presence of a localized defect on it, a Gaussian ridge. The rms height of the random surface was approximately 0.37 μm, and its transverse correlation length was 2.5 μm. The ridge was defined by the profile

function $P exp(-x_1^2 / b^2)$, where $P \cong 1.0$ μm and $b = 3.2$ μm. The correlation function of the intensity of the light scattered from the surface should display a strong correlation when the condition

$$sin\theta_s - sin\theta_0 = sin\theta'_s - \theta'_0 \qquad (2.7\text{-}1)$$

is satisfied. This is the condition for the occurrence of the memory and reciprocal memory effects. In the experiment θ_0 was kept fixed and equal to θ'_0, while the correlation function was measured as a function of $\Delta\theta_s = \theta_s - \theta'_s$ for a fixed value of θ'_s. The peak in the correlation function at $\Delta\theta_s = 0$ decreased more slowly with increasing $\Delta\theta_s$ for the random surface with a defect than for the random surface without a defect, demonstrating the sensitivity of the angular intensity correlation function to the presence of the defect.(24)

2.8 Random Surfaces that Suppress Single Scattering

In theoretical studies it is possible to separate the contribution of single-scattering processes to the mean intensity of the light that is scattered incoherently from the contribution of multiple-scattering processes. However, it is not so easy to achieve experimentally. In the case of scattering of light from two-dimensional random surfaces the in-plane, cross-polarized scattering of p-polarized light suppresses the single-scattering contribution to the mean intensity of the light that is scattered incoherently. In the case of scattering of light that is incident normally upon a weakly rough one-dimensional random metal surface the use of a surface whose roughness is characterized by a power spectrum $g(|k|)$ that vanishes identically for $|k| < K_{min} \leq \omega/c$ eliminates the contribution of single-scattering processes to the mean intensity of the incoherent component of the scattered light for scattering angles that are smaller in magnitude than $\sin^{-1}(ck_{min}/k\omega)$. However, such surfaces are difficult to fabricate.

We have performed a method for numerically generating a one-dimensional random surface, defined by the equation $x_3 = \zeta(x_1)$, that suppresses single-scattering processes in the scattering of light from the surface within a specified range of scattering angles. Rigorous numerical calculations of the scattering of light from surfaces generated by this approach show that the single-scattering contribution to the mean scattered intensity is indeed suppressed with that range of angles.(25) This method is not restricted to generation of weakly rough surfaces. Surfaces with a different form of the pdf $f(\gamma)$, have been fabricated successfully in the laboratory, and their fabrication appears to be simpler than that of surfaces characterized by a West-O'Donnell power spectrum.

3.0 LIST OF PUBLICATIONS

3.1 Journal Publications

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